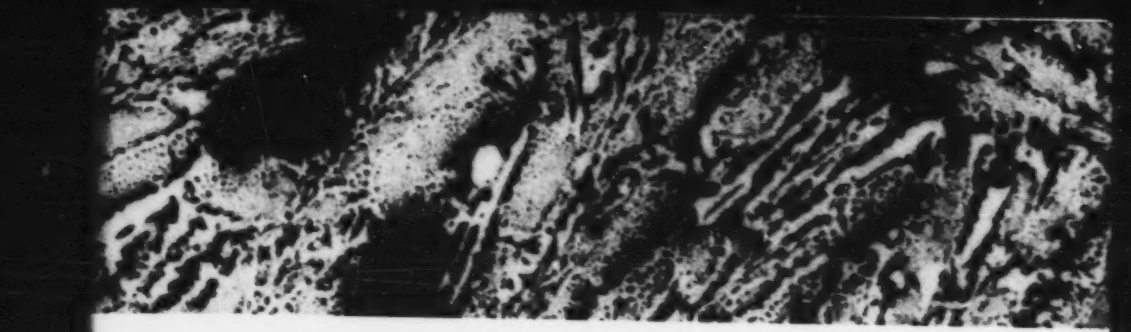


Cast Irons from Les Forges du Saint-Maurice, Quebec A Metallurgical Study

Henry Unglik

Environment Canada Parks Service
Environnement Canada Service des parcs

Cast Irons from Les Forges du Saint-Maurice, Quebec A Metallurgical Study

Henry Unglik

Studies in Archaeology
Architecture and History

National Historic Parks and Sites
Parks Service
Environment Canada

91-00625/

©Minister of Supply and Services Canada 1990.

Available in Canada through authorized bookstore agents and other bookstores, or by mail from the Canadian Government Publishing Centre, Supply and Services Canada, Hull, Quebec, Canada K1A 0S9.

Published under the authority
of the Minister of the Environment,
Ottawa, 1990

Editing and design: Jean Brathwaite
Production: Lucie Forget and Rod Won

Parks publishes the results of its research in archaeology, architecture, and history. A list of publications is available from Research Publications, Parks Service, Environment Canada, 1600 Liverpool Court, Ottawa, Ontario K1A 0H3.

Canadian Cataloguing in Publication Data

Unglik, Henry

Cast irons from les Forges du Saint-Maurice, Quebec: a metallurgical study

(Studies in archaeology, architecture and history,
ISSN 0821-1027)
Issued also in French under title: Fontes provenant des Forges du Saint-Maurice.
Includes bibliographical references.
ISBN 0-660-13598-1
DSS cat. no. R61-2/9-48E

1. Forges du Saint-Maurice (Quebec) — Antiquities. 2. Ironworks — Quebec (Province) — Saint Maurice River Valley — History. 3. Cast-iron — Analysis. I. Canadian Parks Service. National Historic Parks and Sites. II. Title. III. Series.

FC2945.SA38 1990 672.09714'451 C90-098638-7
F1054.S33U53 1990

Contents

5 Summary

7 Acknowledgments

9 Introduction

11 Historical Background

15 Metallurgical Examination of the Cast Irons
18 Examination Procedures
21 Chemical Analysis
21 Hardness
21 Macrostructure
23 Microstructure
23 Grey Irons
26 Mottled Irons
28 White Irons

31 Characterization of the Cast Irons
31 Effect of Composition
33 Foundry and Mechanical Properties

37 Method of Manufacture

41 Technological Development of the Ironworks

43 Glossary of Metallurgical Terms

51 References

Summary

Twelve artifacts recovered from Canada's first ironworks at Les Forges du Saint-Maurice, Quebec, were subjected to metallurgical examination. The investigation showed the material to be cast iron characterized by a wide variety of structures typical of grey, white, and mottled cast irons.

The structure of the grey irons is that of a phosphoric cast iron with flake graphite in a pearlitic matrix. They have hardness and strength comparable to modern grey iron, excellent fluidity, and little or virtually no solidification shrinkage. Their composition falls within range of the current engineering specifications for use at elevated temperatures, especially for superior thermal shock resistance. The ledeburitic white irons and the pearlitic mottled irons with massive cementite and phosphide eutectic are very hard and brittle and show considerable shrinkage.

The St. Maurice cast irons have (close to) eutectic compositions and liquidus temperatures ranging from 1050 to 1150°C. Most of the material was produced from high-phosphorus iron ores in a charcoal blast furnace that must have operated at low temperatures. It is a cold-blast charcoal iron. The cast-iron artifacts were found to have considerably higher carbon content, and generally higher manganese and phosphorous contents, than found in European or American cast irons. The content of silicon is similar and that of sulphur low, as would be expected for charcoal iron. The molten iron probably was ladled from the open forehearth of the furnace and poured directly into prepared moulds on the casthouse floor. The grey irons were cast from near the melting temperature, close to 1200°C, most likely into loam or sand moulds. The white irons were poured at a higher temperature and probably cast into chilled moulds.

The differences in structure, composition, and technology were actually linked to the four different occupational periods of Les Forges: I, 1667–1760; II, 1760–1800; III, 1800–1850; and IV, 1850–1883. The cast irons from period I are of varying structure. With one exception, the iron from periods II and III is white or mottled, most with a very high total carbon content. During these two periods a high proportion of charcoal fuel must

have been used for smelting in the blast furnace. In periods I or II the type of ore used to manufacture the cast irons changed from low- to high-phosphorous ores. In transition between periods III and IV there was a change in casting technology from chilled moulds to sand moulds. The last period (IV) distinguished itself in phosphoric grey iron plates of uniform structure and composition.

Submitted for publication 1987, by Henry Unglik, Historic Resource Conservation Branch, Parks Service, Environment Canada, Ottawa.

Acknowledgments

I wish to express my appreciation to J. Stewart, J. Moore, and M. Salmon of the Historic Resource Conservation Branch, Canadian Parks Service, Ottawa, for reading the manuscript and offering many valuable comments. Many thanks are also due to André Bérubé, History and Archaeology, Quebec Region, Canadian Parks Service, Quebec City, who graciously reviewed the historical part of the paper. Special acknowledgments are made to my fellow workers J. Stewart, C. Costain, and A. Douglas for their expert chemical analyses of cast irons, to G. Vandervlugt for his assistance in producing an interesting set of photographs, to Carol Piper for her work on Figure 1, and to the Canadian Parks Service for its constant support.

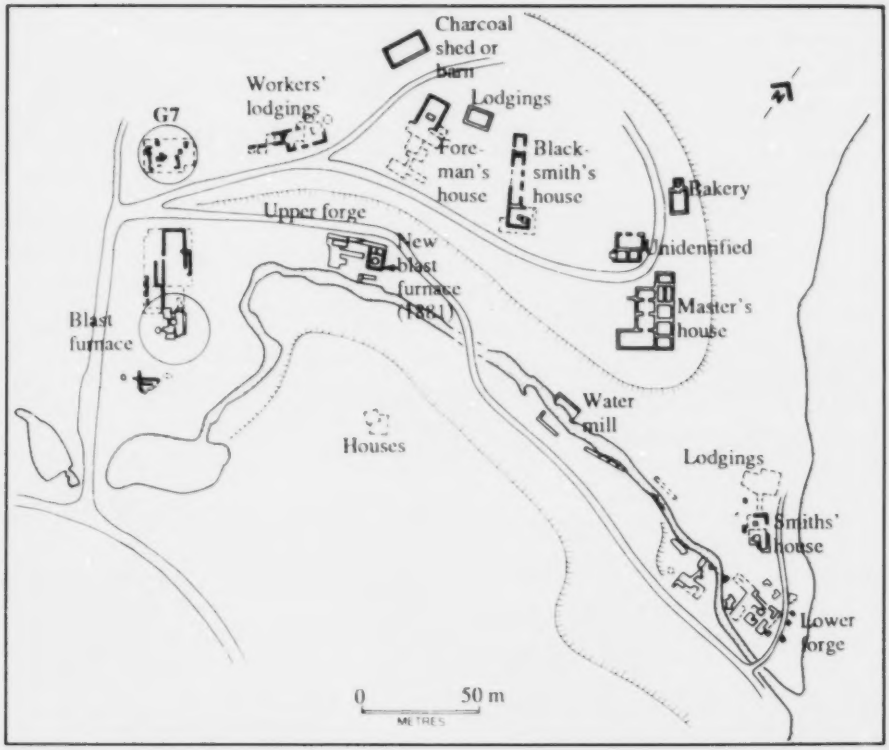
Introduction

This is an account of metallurgical investigation carried out on 12 cast-iron artifacts from Les Forges du Saint-Maurice, Canada's first ironworks.

The 18th- to 19th-century iron-working site is situated near Trois-Rivières, Quebec, and has been extensively excavated by the Canadian Parks Service over the past ten years. The material was recovered from a domestic area north of the blast furnace (*see* Fig. 1) with a relative chronology covering the four different occupational periods.

The macrostructure, microstructure, hardness, and chemical analysis of grey, mottled, and white irons are presented with a short history of the site. The results of the examination are used to characterize the material: its composition, structure, and foundry and mechanical properties. The method of manufacture of the cast irons and the technological development of the ironworks are considered. Comparisons are drawn between the cast irons from Les Forges and cast irons from other iron-working centres.

A short version of this work was published in the *Journal of the Historical Metallurgy Society* (Unglik 1987).



1 Excavations at Les Forges du Saint-Maurice ironworks. The cast-iron artifacts discussed in this report were recovered from area G7, a domestic area north of the blast furnace.

Historical Background

Information concerning Les Forges du Saint-Maurice comes from two main sources: historical records (Swank n.d.; Harrington 1874; Bérubé 1983, 1984 [pers. com.]; Miller 1968; Trottier 1980; Beaudet 1983) and archaeological research carried out at the site by the Canadian Parks Service (Cox 1977; McGain 1977; Nadon 1977).

Les Forges du Saint-Maurice was founded on the Saint-Maurice River near Trois-Rivières, halfway between Montreal and Quebec City on the St. Lawrence River. Iron ore was discovered in the vicinity of Trois-Rivières as early as 1667 and the mining of the ores started in 1672. The ironworks were formally established in 1730 when Louis XV granted a royal commission to a resident of New France, François Poulin de Francheville, who was a Montreal merchant and the owner of the Saint-Maurice seigneury. The first, short-lived, effort of iron smelting directly from ore was carried out in a Catalan-type forge constructed in 1733. Using the direct-process technology copied from New England, the Francheville bloomery forge produced during its entire operation (in 1734) one ton of wrought-iron bars. The small output hardly exceeded nine kilograms of iron per day.

In 1735 a new company, Cugnet et Cie., was formed to build a profitable enterprise using the indirect reduction process. The ironmaster, Olivier de Vézin, soon arrived from France to take charge of Les Forges. The construction of a blast furnace with a capacity for daily output of 2.5 tons of pig iron began in 1736. In the same year the master's house, the lower forge, and the lodgings for the workers were started (Fig. 1). The smelting of bog-iron ore in the charcoal-fired blast furnace was carried out regularly by 1738. Two finery hearths were erected in 1736 in the lower forge and two in 1739 in a second forge (the upper forge). In 1740 the blast furnace was 4.5 metres high. A water wheel operated wooden bellows, and a cold blast was supplied by a tuyère. All the necessary raw materials for the manufacture of iron — i.e., pure bog ore, plentiful charcoal, and good-quality limestone — were

found nearby. Charcoal from deciduous trees was used for the furnace and from coniferous for the forges. Iron was produced in the form of castings obtained directly by pouring molten iron from the blast furnace into prepared moulds. These castings were pots, kettles and other hollow ware, stoves, and such military equipment as cannons, mortars, and cannon balls. Wrought-iron bars of various kinds were manufactured at the hammer forge. A regular labour force of about 30 men plus about 240 seasonal workers was employed at Les Forges in 1742. Cugnet et Cie. went bankrupt in 1741 and the ownership of Les Forges reverted to the Crown in 1743.

In 1760 Canada passed into the possession of the British and with it Les Forges du Saint-Maurice. Production ceased completely in 1765 after five years of scaled-down operations; it was successfully resumed between 1767 and 1793. In 1793 Matthew Bell became one of the leaseholders of Les Forges, which thrived for most of the 53 years of his leadership. In 1815 the total labour force reached about 300 men, including about 50 skilled workers living in the St. Maurice community, and the rate of production increased substantially. Heating stoves, large potash kettles, "machines for mills," and ploughshares were turned out in large numbers. In the 1820s a cupola furnace or an air furnace was installed in the area of the blast furnace. By that time only some pig iron went for export.

In 1846 the British government sold the ironworks to Henry Stuart. A period of technological changes followed, mainly modernization of the blast furnace. Its dimensions were increased and it was equipped with water-cooled tuyères, a hot-blast stove, and an air compressor powered by a turbine. The daily production of the blast furnace was doubled to more than four tons, of which ten per cent was white and ten per cent mottled iron. Three tons of ore and one ton of charcoal were required to make one ton of iron.

Les Forges began to decline roughly a decade before John McDougall bought the ironworks in 1863. Iron castings production was abandoned. Very little wrought iron was refined in a Walloon hearth, and most of it was employed by the blacksmith for local use. After production of wrought iron ceased in the late 1860s, cast iron remained the only product of Les Forges. This high-quality metal was sent to large foundries in Montreal for making railway car wheels. The blast furnace was about 9 metres high in 1873, and the internal diameter at the hearth was 0.75 metre, at the bosh 2 metres, and at the throat 1 metre. It had two tuyères and a cold blast. Due to an economic depression the plant was shut down in 1877, although it reopened in 1880. Construction of a new, modern blast furnace a year later, in 1881, did not revive the industry.

The original blast furnace was finally abandoned in 1883, and the ironworks was closed due to the increased cost of raw materials, competition within the trade, and the serious financial problems of John McDougall's successor, George McDougall. Swank, writing in 1892 about "The First Iron Works in Canada," states (n.d.: 351): "at the time of its abandonment in 1883 the St. Maurice furnace was the oldest active furnace on the American continent."

The four archaeological periods at Les Forges can be related to the three periods of Canada's political history — the New France period (1604–1760), the British North America period (1763–1867), and the first years of Dominion of Canada (post-1867). Briefly outlined below is the ironwork's technological development.

I	**1667–1760**	
	1667	Iron ore discovered in the vicinity of Trois-Rivières.
	1672	Mining of ore started.
	1730	Les Forges founded by royal commission.
	1732–1734	Direct process copied from New England. Production of bloomery iron in the Catalan forge slightly exceeding nine kilograms per day. Total production of one ton of wrought iron.
	1736	Blast furnace and two finery hearths (the lower forge) erected.
	1738–1760	Indirect process in a charcoal blast furnace accompanied by two large forges. (Upper forge built in 1739.) Daily production 2.5 tons of cast iron. One of Les Forges' most successful periods of operation. Production of pots, kettles, stoves, cannons, mortars, and wrought-iron bars.
II	**1760–1800**	
	1760–1793	Intermittent operations.
III	**1800–1850**	
	1793–1846	Great prosperity in the first part and declining performance in the last part of this period.
	1793–1815	Production of large potash kettles, heating stoves, ploughshares, cauldrons, "machines for mills," anvils, tools, various kinds of castings, also wrought-iron bars and pig iron.

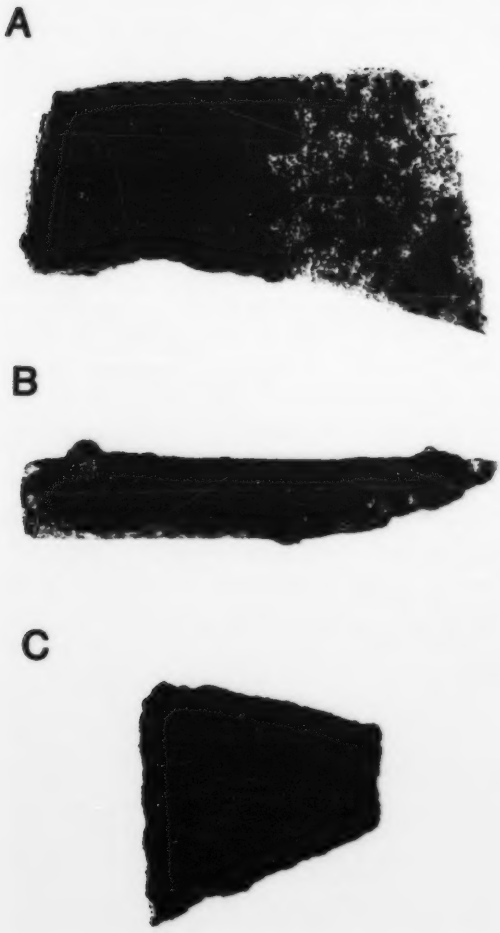
	1820s	Introduction of a cupola or air furnace; only small quantities of pig iron went for export.
IV	**1850–1883**	
	1846–1883	The final years, a period of technological change but only intermittent operation. Daily production rose to four to five tons after the renovation of the blast furnace, mainly by increasing its dimensions. A hot-blast stove and an air compressor were also introduced around the blast furnace.
	1860s	Production of wrought iron as well as of iron castings ceased completely.
	1873–1883	Intermittent operations limited to production of cast iron shipped to Montreal to foundries making railroad cars.
	1881	A second charcoal-fired blast furnace was built. It was of modern design with a hot blast and three water-cooled tuyères.
	1883	Original blast furnace abandoned. Final closing of the ironworks.

Metallurgical Examination of the Cast Irons

The surfaces of the cast-iron artifacts from Les Forges were covered by tightly adhering sand underneath which corroded metal with dark brown, compact corrosion products was visible. Designation, size, and chronology of the artifacts are given in Table 1.

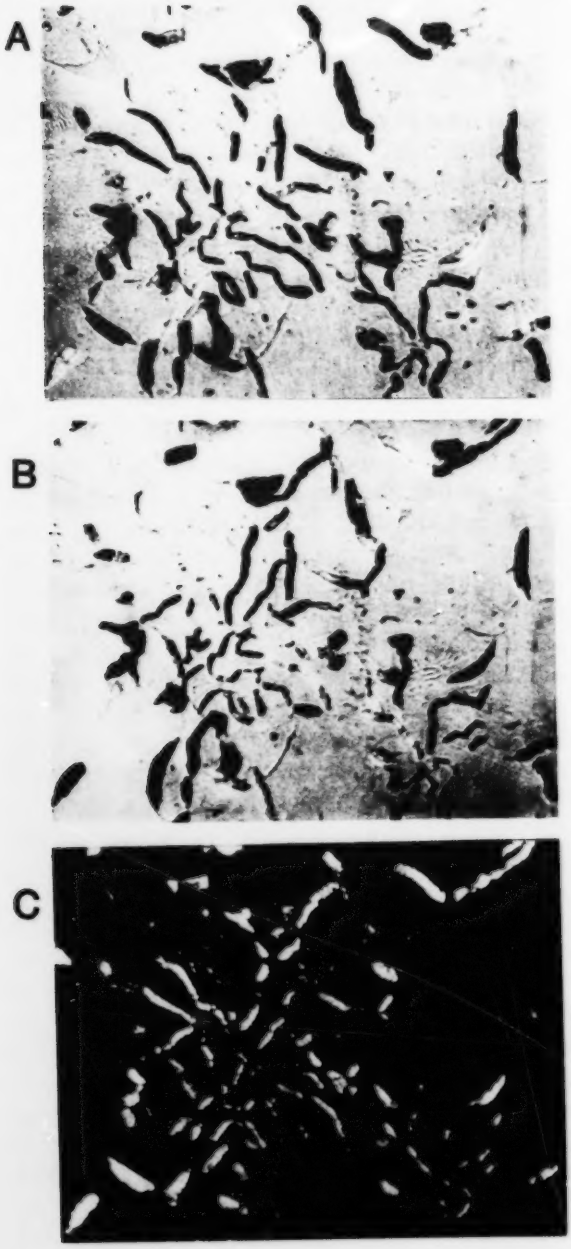
Table 1
Description of the Cast-Iron Artifacts

Archaeological Period	Provenance No.	Code No.	Artifact	Approx. Size (cm)	Thickness (cm)
I	25G7A40	C1	plate	23 x 16	1.5
1667–1760	25G7E9	C2	sprue	7 x 8	1.5
	25G7E9	C3	scrap frag.	6 x 4.5	0.6
II	25G7C15	C4	sprue	5.5 x 7	1.5
1760–1800	25G7B47	C5	runner	18 x 6	1.2
	25G7E8	C6	sprue	5.5 x 5.5	3.0
III	25G7B30	C7	sprue	9 x 10	2.0
1800–1850	25G7C8	C8	runner	17.5 x 3	1.5
	25G7F5	C9	sprue	8 x 11	2.0
IV	25G7B4	C10	plate	10 x 4.5	1.0
1850–1883	25G7B23	C11	plate	12 x 10	0.8
	25G7B5	C12	plate	9 x 5	0.8



2 General view of selected cast-iron artifacts, at x 0.5: *A*, grey iron plate; *B*, mottled iron runner; *C*, white iron sprue.

3 *Opposite* Optical anisotropy of graphite flakes under polarized light: *A*, plane polarized light; *B*, at 90° position; *C*, between crossed polars.


A
B
C

Examination Procedures

Examination procedures included visual observation, macroscopic examination, hardness testing, chemical analysis, microscopic examination, and microhardness measurements. The cast-iron artifacts were sectioned, using a diamond blade, in the direction parallel to the longest axis of casting (the general appearance of selected finds is shown in Figure 2). Macroetching in ten per cent ammonium persulphate was carried out on all cast-iron sections to reveal casting defects and the segregation and structure of large areas. Etching in Stead's reagent was done on grey irons to reveal eutectic cells, a cell structure governed by the austenite/graphite eutectic transformation. The surface fractures and etched sections were examined both with the unaided eye and at low magnification using a stereoscopic microscope.

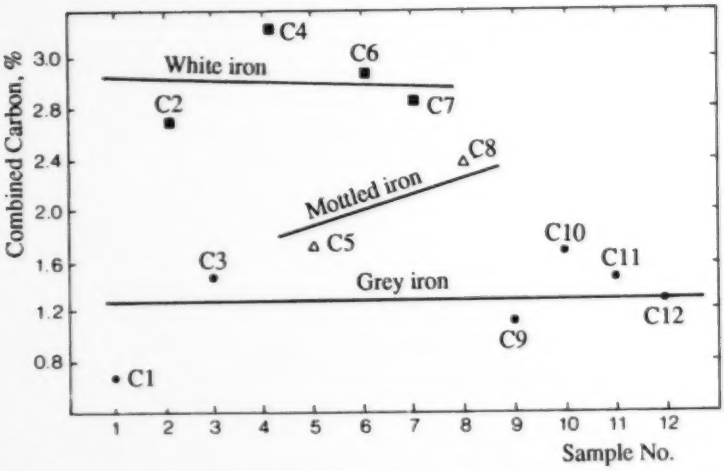
Hardness measurements were taken on polished sections using the Rockwell method. Rockwell B (1/16-inch-diameter ball at 100-kilogram load) was used for the soft material and Rockwell C (diamond pyramid, 150-kilogram load) for the hard material. The values obtained have been converted to standard Brinell HB 10/3000 as approximate equivalent hardness according to the American Society for Testing and Materials (ASTM) Standard E 140. Drillings from the sections prepared for macroscopic examination were analyzed by wet chemistry, atomic absorption spectroscopy, and colourimetric methods.

Polarized light and reflex plechroism effects (Morrogh 1941a: 199f.) were used to determine if graphite flakes had been correctly polished. Viewed under ordinary illumination, graphite flakes appeared to have a uniform brownish-grey colour. Under plane polarized light some graphite flakes appeared light, some dark, and some intermediate (Fig. 3*A*); on rotating the specimen stage through 90 degrees the formerly dark flakes became light and vice versa (Fig. 3*B*). Under crossed polars, graphite flakes in the same field have been seen at bright positions (Fig. 3*C*). Poorly polished graphite flakes do not reproduce the correct polarization characteristics.

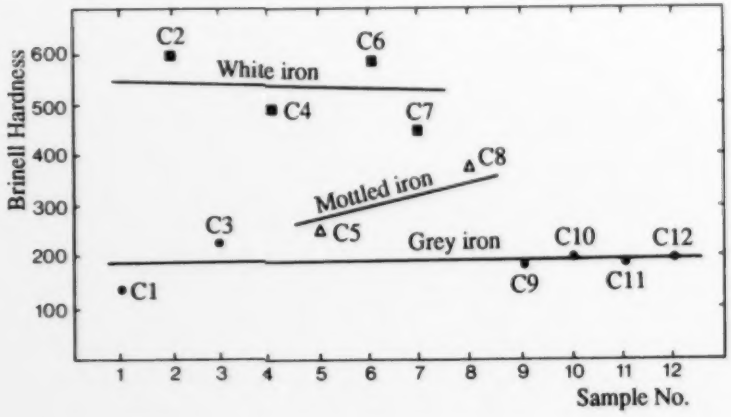
The microspecimens were etched in four per cent nital to reveal the cast-iron structure and in Murakami's reagent to distinguish between iron phosphide and cementite. The microstructure of polished and etched sections was studied by reflected-light microscopy (Leitz "Orthoplan") at magnifications of 100, 500, and 1000 diameters. Graphite flake shape, size, and distribution were determined at magnification of 100 diameters in accordance with ASTM Standard A 247. Relative hardness of the microcon-

Table 2
Chemical Analysis of the Cast Irons

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
Total carbon	3.45	3.91	3.91	3.95	4.18	4.51	4.21	3.81	3.77	3.79	3.71	3.88
Graphitic carbon	3.18	1.60	2.83	0.89	2.87	1.81	1.60	1.80	3.03	2.53	2.63	3.01
Combined carbon	0.27	2.31	1.08	3.06	1.31	2.70	2.61	2.01	0.74	1.26	1.08	0.87
Silicon	0.46	0.65	0.78	0.67	0.49	0.48	0.44	0.67	0.70	0.84	0.77	0.44
Manganese	0.46	0.65	0.94	0.13	1.42	0.90	1.38	1.46	0.91	0.12	0.11	1.00
Phosphorus	0.19	0.28	0.11	0.57	0.85	0.20	1.31	1.25	0.63	0.70	0.66	0.70
Sulphur	0.029	0.025	0.027	0.035	0.034	0.039	0.031	0.020	0.034	0.032	0.040	0.051
Chromium	0.003	0.003	0.005	0.007	0.006	0.007	0.007	0.005	0.006	0.004	0.004	0.005
Nickel	0.004	0.007	0.006	0.006	0.005	0.005	0.005	0.004	0.004	0.003	0.002	0.004
Copper	0.001	0.004	0.002	0.004	0.002	0.003	0.004	0.003	0.001	0.001	0.001	0.001
Titanium	0.02	0.03	—	0.02	0.03	0.02	0.02	0.03	0.06	0.03	0.02	0.02



4 Groupings of the cast irons according to combined carbon content. Circles indicate grey irons; triangles, mottled irons; and squares, white irons.



5 Groupings of the cast irons according to hardness.

stituents was measured using a Vickers-type microhardness tester (Leitz "Miniload") with a diamond pyramid indenter under 50-gram load.

Chemical Analysis

The results of chemical analysis (Table 2) show that with few exceptions the carbon content is higher and the silicon content is considerably lower than those usually found in modern cast iron (cf. Table 5). Phosphorus is often above the range of modern practice, while sulphur is lower than would be found now. The generally high manganese content shows great variation and so does phosphorus, though to a lesser extent. The remaining elements (Cr, Ni, Cu, and Ti) are present only in trace amounts.

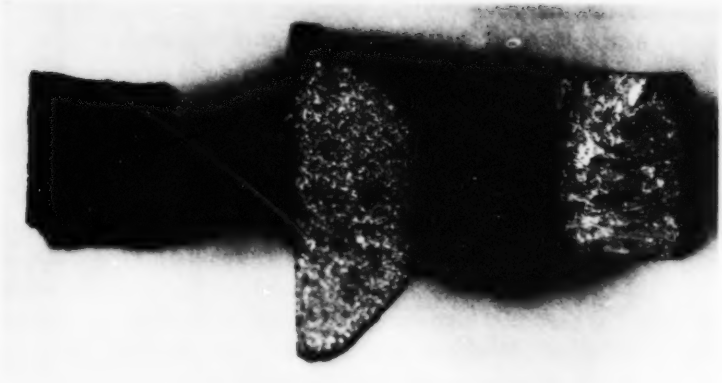
Chemical analysis revealed, in addition, that the carbon in the cast irons is partially graphitic and partially combined. The well-marked physical distinctions of the three types of cast iron (grey, white, and mottled) depend on the amount of combined carbon present in the iron, which in turn is influenced by cooling rate and primary microstructure. Figure 4 and Table 4 show that the artifacts fall into the categories of grey, mottled, and white iron.

Hardness

The results of hardness testing are listed in Table 3. It is not surprising that plotting the hardness values of the individual artifacts (Fig. 5) reveals groupings of cast iron similar to those obtained on the basis of combined carbon content. The hardness values for the artifacts in each group (Table 4) correspond to the typical hardness values for grey iron (130–250 HB), mottled iron (250–450 HB), and white iron (450–600 HB). The hardness of all the grey iron artifacts (except C1) approximates the hardness of commercial pearlitic cast iron. C1 has the lowest hardness value (140 HB) and is typical of annealed ferritic grey iron.

Macrostructure

The appearance of the surface fractures of grey, mottled, and white irons is shown in Figure 6. All three types of cast iron typically show brittle fractures, exhibiting little or no evidence of plastic deformation. It can be



6 Surface fracture of (left to right) grey, mottled, and white cast irons, at x 2.

seen in Figure 6 that the fractured surface of the grey iron sample is characteristically grey, whereas the white iron sample has a white crystalline appearance. The fracture surface of the mottled iron sample is intermediate between the grey and white iron samples.

The macrostructure of grey cast irons is characterized by a grey or dark surface with no visible defects (Fig. 7*A*) and a fine network of eutectic cells of phosphorus (Fig. 8*A*). The Stead's reagent selectively darkened low-phosphorus regions in the irons and left high-phosphorus regions unattacked and light. The mottled irons show the presence of shrinkage porosity (Fig. 7*B*) and a shiny surface of massive cementite with large proportions of dark areas; i.e., numerous grey spots of graphite concentration (Fig. 8*B*).

In the white irons the presence of casting defects such as shrinkage cavities, interdendritic cracks, or pores is even more extensive than in the mottled irons (Fig. 7*C*); here the shiny surface of massive cementite contains only a few grey spots (Fig. 8*C*). The columnar crystals, radiating toward the centre of the casting, have grown perpendicularly to the faces of the mould. Planes of weakness at the crystals' junctions were easily noticeable.

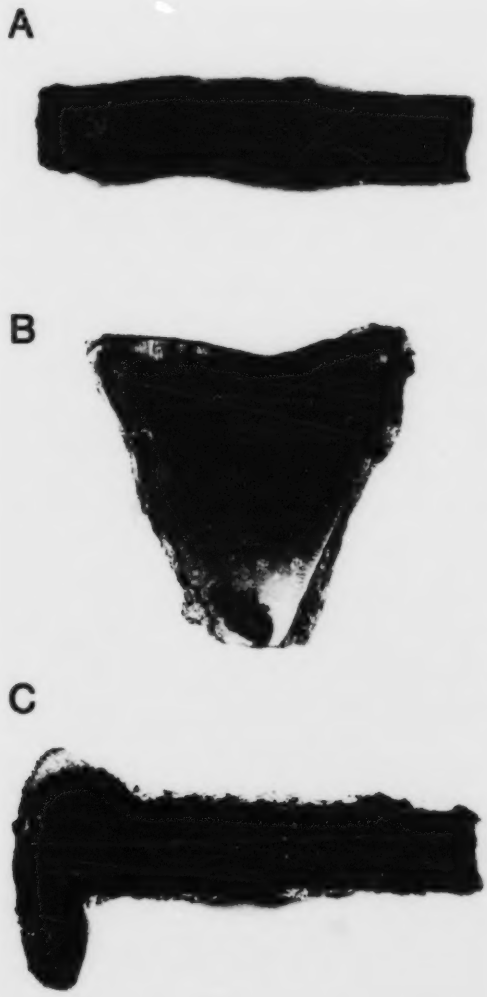
Microstructure

Microscopic examination revealed that six artifacts (C1, C3, C9, C10, C11, and C12) have structures typical of grey iron, four artifacts (C2, C4, C6, and C7), typical of white iron, and the remaining two artifacts (C5 and C8), typical of mottled iron.

Grey irons. The structure of the grey iron specimens is that of hypoeutectic, phosphoric cast iron with flake graphite in pearlitic matrix. As illustrated in Figure 9*A*, graphite occurs in the form of flakes of considerable length, random orientation, and uniform distribution, with some flakes in rosette groupings. In all grey iron artifacts except C1, the relatively hard pearlite (385 HV_{50}) consists of both fine and coarse alternating lamellae of light-etching ferrite and darker cementite (Fig. 9*B*). The best strength in the ordinary range of grey irons is associated with a pearlite matrix. The pearlitic matrix of the specimens enhances the quality of the grey iron plates, contributing to higher hardness values and greater strength and wear resistance. The presence of free cementite in C3 accounts for its somewhat higher hardness value (228 HB).

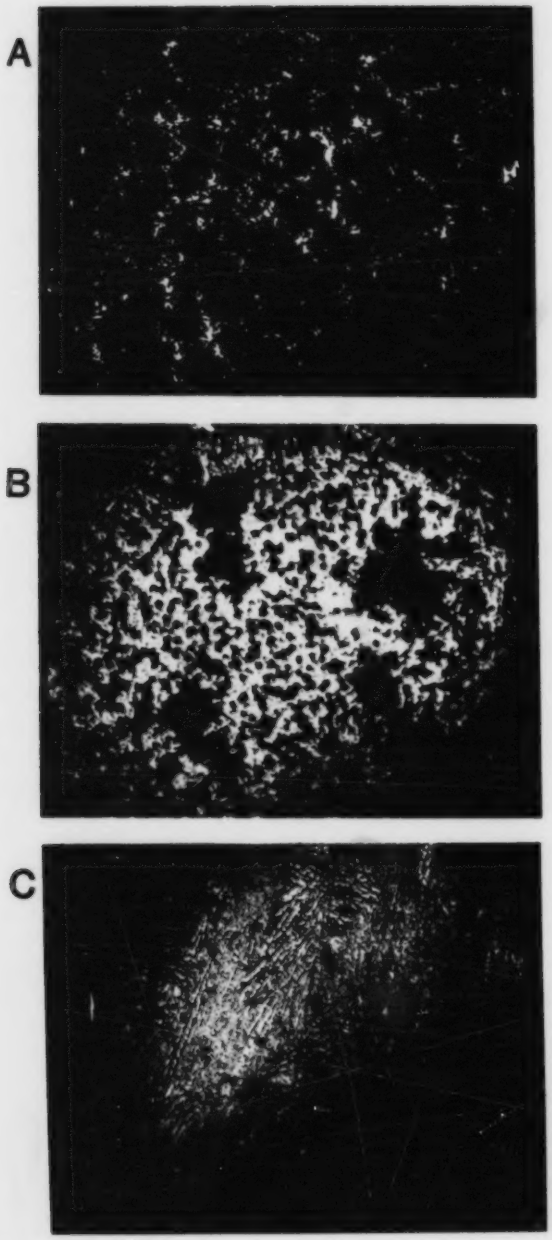
C1, a plate, contains, in addition to regions of lamellar pearlite, large and relatively soft areas of spheroidized pearlite (204 HV_{50}) showing globular carbide particles uniformly dispersed throughout the ferritic matrix (Fig. 9*E*). Spheroidized carbides were formed during prolonged heating at about the critical temperature (723°C) followed by slow continuous cooling. As a result, the hardness value of the material decreased significantly (to 140 HB). The presence in the structure of lamellar and spheroidized pearlite indicates that the C1 plate was subjected to heating at uneven temperatures.

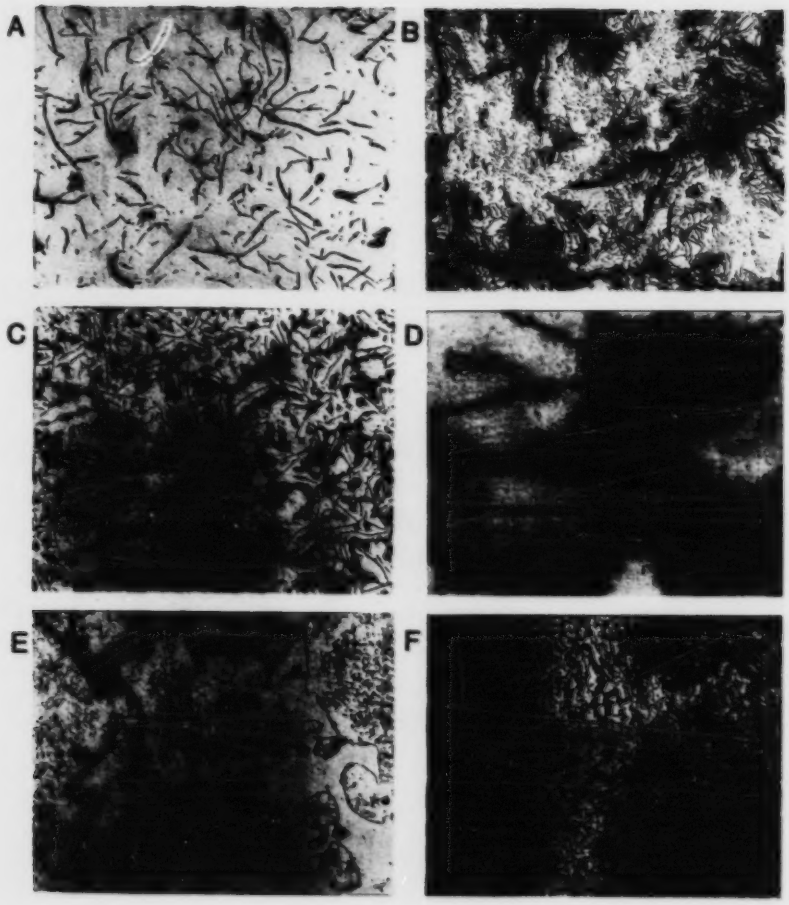
Phosphide eutectic, with its characteristic lenslike shape, is another major constituent present in the grey irons. Selective etching with Murakami's reagent darkened the phosphide phase occurring in the interdendritic regions, which were the last to solidify (Fig. 9*C*). The high phosphorus content introduced sufficient amounts of the phosphide phase to form a discontinuous fine network following the austenite/graphite eutectic cell boundaries. The ternary nature of the phosphide eutectic is demonstrated at high magnification in Figure 9*D*. It shows that this hard and brittle intermetallic compound, called steadite (963 HV_{50}), actually consists of ferrite (or pearlite) in a duplex matrix, being a mixture of iron phosphide and iron carbide. The presence of a large amount of steadite in pronounced network formation increases hardness, brittleness, and wear resistance.



7 Macrostructure of cast irons etched in ammonium persulphate: *A*, grey iron, at x 2; *B*, mottled iron, at x 1.5; *C*, white iron, at x 1.5.

8 *Opposite* Macrostructure of cast irons etched in Stead's reagent: *A*, grey iron, at x 1.5; *B*, mottled iron, at x 8; *C*, white iron, at x 8.


A
B
C

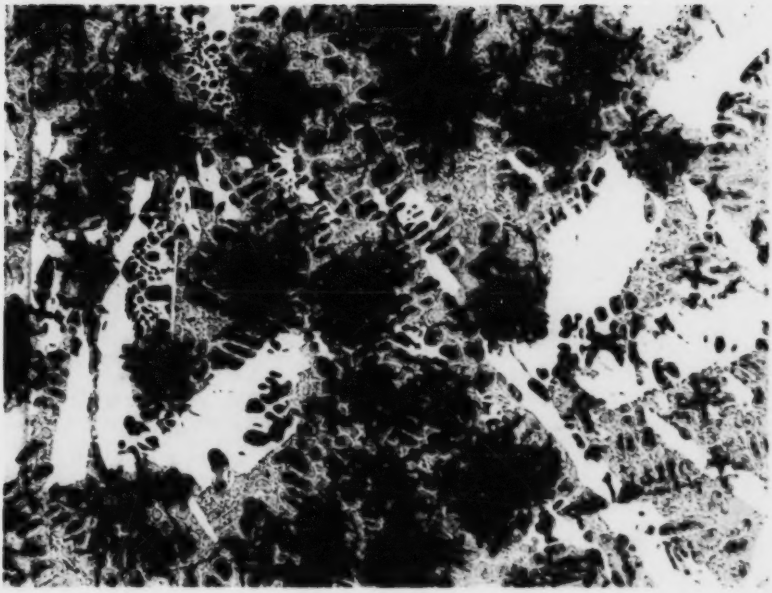


9 Microstructure of grey irons: *A*, not etched, x 100; *B*, 4% nital, x 500; *C*, Murakami's reagent, x 100; *D*, Murakami's reagent, x 1000; *E* and *F*, 4% nital, x 100.

The fine cellular structure evident in these high-phosphorus grey irons represents its mode of solidification and is similar to the grain size of wrought iron or single-phase steel. The cell size has been shown to have a distinct bearing on mechanical properties as well as on the shrinkage characteristic of the iron (Bailey and Samuels 1971: 126, 128, 133). Tensile strength increases as cell size decreases. At the same time, occurrence of porosity defects is aggravated by an increase in the number of eutectic cells, though no porosity was observed in the grey iron macrosections except in C9.

Besides the major phases, the presence of a surface chill zone was observed in plates C1, C3, and C12, as were some free cementite in plates C1 and C3 and a considerable amount of nonmetallic inclusions in the structure of most grey irons. The cooling rate was most rapid where molten metal had been in contact with the mould walls, causing the cementite columns to be favourably oriented with respect to the direction of heat flow (Fig. 9*F*). The nonmetallic inclusions of regular shape presented in bright field a typical uniform dove-grey colour (Fig. 9*E*) and between crossed polars remained dark in all positions of the microscope stage. It is generally accepted that the dove-grey idiomorphic inclusions in cast iron are manganese sulphide. This is supported by the fact that most of the grey iron artifacts have enough manganese to balance the sulphur content.

Mottled irons. The mottled irons consist of graphite flakes, free cementite, and a considerable amount of phosphide eutectic in a pearlite matrix (Fig. 10). Graphite appears in the form of flakes characterized by rosette groupings and random orientation (Form VII, Type B, Size 4). Type B graphite distribution is common only in mottled cast irons. The low eutectic nucleation resulted in a large cell size so that outward graphite flake growth formed a radial pattern. Lamellar pearlite in the mottled irons, finer than in the grey irons, shows consequently higher microhardness values (437 HV_{50}). Free cementite, a very hard and brittle phase (1121 HV_{50}), occurs in the form of randomly oriented large and small columnar crystals. The significantly higher hardness value of artifact C8 (378 HB) compared to that of C5 (261 HB) is clearly due to the fact that the former contains much more free cementite than the latter. This mottled structure is a result of borderline conditions in the artifacts — i.e., an intermediate cooling rate. If C5 and C8 had been cast in slightly larger sections they would have solidified grey.

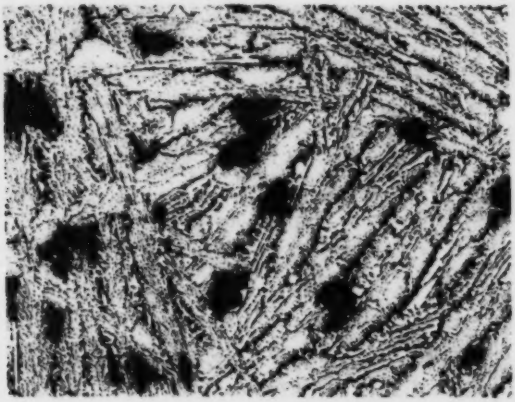


10 Microstructure of mottled iron, 4% nital, x 100.

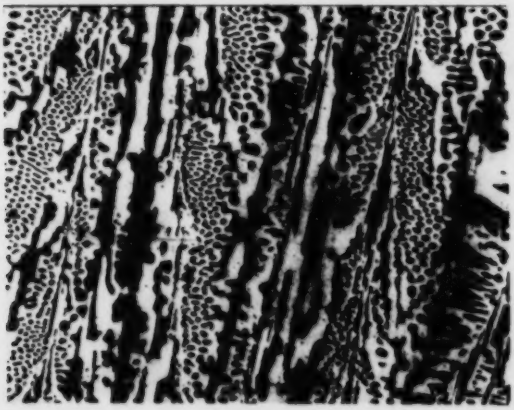
11 *Opposite* Microstructure of white irons, 4% nital: *A*, x 100; *B*, x 500; *C*, x 100.

White irons. Most of the white irons are composed of a hard eutectic mixture of cementite and pearlite known as ledeburite (913 HV_{50}) and a small amount of graphite (Fig. 11*A*). The irregular graphite pockets and aggregates show signs of deterioration and have non-uniform distribution. The small nests of graphite were formed as a result of the very high carbon content. Their presence demonstrates the difficulty of stabilizing the massive cementite in spite of low silicon and rather high phosphorus or manganese contents. At higher magnification, details of the well-formed ledeburite eutectic became evident (Fig. 11*B*), showing white featureless crystals of cementite and the rod-like nature of the austenite constituent transformed on cooling to pearlite. The structure of C7 (Fig. 11*C*) shows a high degree of degeneration of ledeburitic eutectic, taking the form of

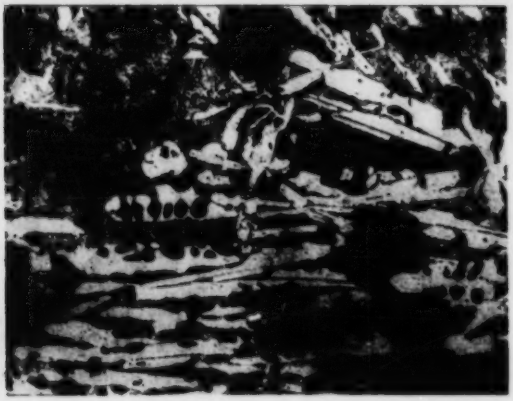
A



B



C



massive, primary cementite from which the other eutectic constituent (pearlite) is absent. At the eutectic temperature it is not unusual for ledeburite to be separated completely, with eutectic austenite added to the primary austenite dendrites, leaving behind columns of massive free cementite. According to Bailey and Samuels (1971: 129), the apparent degeneration in hypoeutectic alloys is progressively produced by increasing additions of phosphorus, which reaches 1.3 per cent in C7.

Characterization of the Cast Irons

Effect of Composition

The main factors influencing the type of primary structure of cast iron — i.e., formation of graphite rather than cementite upon the freezing of the eutectic — are the composition and the rate of cooling governed by thickness of the section, type of mould, and temperature of the tapped metal. For a given composition the rate of cooling from the freezing temperature to about 650°C determines the ratio of combined to graphitic carbon, which controls the type of cast iron. The structure of the matrix, formed in a casting during the eutectoid interval, depends in turn upon the primary structure and the cooling rate through the eutectoid temperature range as well as the composition. In short, the composition plus the rate of cooling determine the structure, mechanical properties, and foundry properties of cast iron.

The carbon content of the eutectic, which is reduced by the presence of silicon and phosphorus, has the most significant effect on the solidification of cast irons. The effect of these three elements is expressed by the carbon equivalent and the degree of saturation, both of which describe how near the cast-iron composition is to the eutectic composition. This is important because as eutectic composition is approached, melting point decreases, fluidity increases, and tensile strength of the solidified cast irons decreases. The carbon equivalent metallurgical significance also lies in the fact that it indicates the mode of solidification of the iron and thus its microstructure.

The calculated values of carbon equivalent and degree of saturation are given in Table 3. The average carbon equivalent value of CE = 4.4 and average degree of saturation of SC = 1.0 show that the cast irons have a eutectic, or close to eutectic, composition; the only three strongly hypereu-

tectic cast irons (SC>1) are C5, C6, and C7. The high carbon equivalent resulted in the formation of malformed and exploded graphite in the white irons. The average content of combined carbon in the cast irons (1 per cent in pearlitic grey irons, 1.7 per cent in mottled irons, and 2.7 per cent in white irons) illustrates, on the other hand, how markedly strength and hardness of cast irons depend on their microstructure — i.e., the form taken by the total carbon — and on the nature of the matrix.

The effect of composition is not confined to carbon only, but includes other major elements found in the cast irons from Les Forges such as silicon, manganese, and sulphur. The extent of the graphitization tendency of silicon is limited here because of its low content and the counteracting effect of manganese. The influence of sulphur needs to be considered relative to its reaction with the manganese. Manganese has a greater affinity for sulphur than iron, forming manganese sulphide, present in the cast irons in the form of small, harmless inclusions instead of iron sulphide, which might cause serious embrittlement. The manganese content is in most artifacts more than sufficient to balance the sulphur content according to the formula $\%Mn = 1.7 \times \%S + 0.15$ (*Gray and Ductile Iron Castings*... 1971: 111). The excess manganese present has little effect on solidification and only weakly retards primary graphitization, but is strongly carbide-stabilizing on eutectoid graphitization and promotes a pearlitic microstructure. The balanced amounts of manganese and sulphur assist in retaining pearlite even when castings are cooled in sand moulds. The amount of sulphur remaining after the sulphur combined with manganese in C4, C10, and C11 is small and should not influence either casting or use properties.

Another pearlite-stabilizing element is phosphorus. The considerable amount of hard and brittle steadite observed in the structure reflects the high percentage of phosphorus found by chemical analysis. Phosphorus hardens and strengthens cast iron to a certain extent and appreciably increases its brittleness. It also has a limited effect in increasing the fluidity and melting range of cast iron, thus improving its castability. Having a high phosphorus content, the examined pig irons are well adapted to the manufacture of medium to light castings not requiring great impact strength. The higher-than-normal phosphorus content improves the heat resistance of the cast irons — i.e., resistance to growth — the retention of mechanical properties, and resistance to scaling (Bailey and Samuels 1971: 132f.). Heat resistance becomes important when cast irons are used above 450°C. Ordinary low-phosphorus grey irons are capable of carrying sustained loads without distortion up to temperatures of 300 to 400°C.

Foundry and Mechanical Properties

To help in characterizing the material from Les Forges, several foundry and mechanical properties were determined on the basis of the composition and section thicknesses of the cast irons (Tables 3, 4). The properties of the cast irons listed in Table 3, including liquidus temperature, solidification shrinkage, and tensile strength, have been directly correlated to the irons' carbon equivalent. The liquidus temperature of the cast-iron artifacts ranges between 1050 and 1150°C. For grey irons it reaches the upper temperature limit, for mottled irons it is close to the centre, and for white irons it takes up the entire melting-temperature range. Looking at the solidification shrinkage values, one can see that readily graphitizible irons (the grey irons) have little or virtually no solidification shrinkage (about 0.1 per cent on average), whereas the white and mottled irons have considerable shrinkage (-2.1 per cent on average). In fact, the presence of shrinkage cavities or porosity, which greatly weakens the metal, was observed mainly in the white and mottled iron artifacts. The tensile strength of the grey irons, estimated on the basis of composition, ranges from 200 to 278 MPa and the compressive strength from 726 to 923 MPa.

Since the same carbon equivalent values may be obtained with different carbon, silicon, and phosphorus contents, the cast irons of constant carbon equivalent but with appreciably different carbon, silicon, and phosphorus contents will not have similar properties. In other words, chemical composition alone is not adequate to designate an iron with specific mechanical properties. For that reason, such mechanical properties as tensile strength and compressive strength, not directly related to the composition of the cast irons, were also estimated on the basis of their hardness.

Tensile strength in psi (TS) and Brinell hardness (HB) of grey iron are related by the equation $TS = 1.82 \times H^{1.85}$, determined on the basis of a statistical study using data from 1553 individual samples (MacKenzie 1946: 1027). For the grey irons, whose hardness values vary from 185 to 228 HB, the approximate calculated tensile strength ranges from 196 to 289 MPa. A similar range of tensile strength values (200 to 272 MPa) was obtained using Krause's relationship (1969: 15).

It can be seen that the tensile strength of the Les Forges grey irons estimated on the basis of composition is practically the same as that calculated on the basis of hardness values. Similarly, the average compressive strength based both on composition (Schneidewind and McElwee 1950:

Table 3
Characterization of the Cast Irons Grouped according to Archaeological Period

Period	Code No.	Type of Cast Iron	Structure		Composition[a] (%)				Foundry Properties				Mechanical Properties		
			Graphite[b]	Phases[c]	Total C	Comb. C	Mn	P	CE[d]	SC[e]	T°[f]	V%[g]	HB[h]	TS[i]	CS[j]
I	C1	Grey	VII A/B 4	P+G+S+(C)	3.5	0.3	0.5	0.2	3.7	0.8	1215	+0.8	140	—	—
	C2	White	V	L+(P+G)	3.9	2.3	0.7	0.3	4.2	1.0	1150	-2.4	601	—	—
	C3	Grey	VII A/B 4	P+G+S+(C)	3.9	1.1	0.9	0.1	4.2	1.0	1150	+0.1	228	278	923
II	C4	White	V/VI	L+(P+G)	4.0	3.1	0.1	0.6	4.4	1.0	1120	-3.8	502	—	—
	C5	Mottled	VII B 4	P+C+G+S	4.2	1.3	1.4	0.9	4.6	1.1	1080	+0.1	251	—	—
	C6	White	None	L+(P+G)	4.5	2.7	0.9	0.2	4.7	1.1	1080	-2.0	590	—	—
III	C7	White	VII	P+C+G+S	4.2	2.6	1.4	1.3	4.8	1.1	1050	-2.4	464	—	—
	C8	Mottled	VII B 4	P+C+G+S	3.8	2.0	1.5	1.3	4.5	1.0	1100	-2.0	378	—	—
	C9	Grey	VII A/B 4	P+G+S	3.8	0.7	0.9	0.6	4.2	1.0	1140	+0.5	187	200	726
IV	C10	Grey	VII A/B 3	P+G+S	3.8	1.3	0.1	0.7	4.3	1.0	1130	-0.5	195	236	825
	C11	Grey	VII A/B 3	P+G+S	3.7	1.1	0.1	0.7	4.2	1.0	1140	-0.3	185	267	911
	C12	Grey	VII A/B 4	P+G+S	3.9	0.9	1.0	0.7	4.3	1.0	1130	+0.4	199	258	886

Notes

[a] Composition range of the remaining elements is Si = 0.4 to 0.8%, S = 0.02 to 0.05%.

[b] Graphite form, type, and size according to ASTM Standard A 247.

[c] P, pearlite; G, graphite; S, steadite; C, cementite; L, ledeburite. Brackets denote a small amount of the microconstituent.

[d] Carbon equivalent, CE = %C + 1/3 x (%Si + %P)
(*Gray and Ductile Iron Castings*... 1971: 109)

[e] Degree of saturation, SC = %C/[4.3 - 1/3 x (%Si + %P)]
(*Gray and Ductile Iron Castings*... 1971: 110)

[f] Liquidus temperature (rounded to the nearest 10°C),
T°C = 1669 - 124 x (%C + %P/2 + Si/4)
(Humphreys 1961: 621)

[g] Solidification shrinkage, V% = 2.0 (%C graph. - 2.80)
(Hamaker, Wood, and Rote 1952: 410)

[h] Brinell hardness HB 10/3000

[i] Tensile strength in MPa (for uninoculated grey iron cast in simple-shaped castings), TS in psi = 10000 [b - 2 x (%C + %Si/3 + %P/4)]
b = 11.68 - 2.3 log (2 x plate thickness in inches)
(Schneidewind and McElwee 1950: 319f.)

[j] Compressive strength in MPa, from TS vs. CS graph
(Schneidewind and McElwee 1950: 326)

Table 4
Characterization of the Cast Irons Grouped according to Type of Cast Iron

Type of Cast Iron	Artifact	Code No.[a]	Structure	Composition[b] (%)				Foundry Properties				Mechanical Properties		
				Total C	Comb. C	Mn	P	CE	SC	T°C	V%	HB	TS (MPa)	CS (MPa)
Grey irons	Plates	C3, C9[c], C10, C11, C12	P+G+S	3.5 3.9	0.7 1.3	0.1 1.0	0.1 0.7	4.2 4.3	1.0	1130 1150	-0.5 0.5	185 228	200 278	726 923
Mottled irons	Runners	C5, C8	P+G+C+S	3.8 4.2	1.3 2	1.4 1.5	0.8 1.3	4.4 4.6	1.0 1.1	1080 1100	-2.0 0.1	251 378	—	—
White irons	Sprues	C2, C4, C6, C7	L+(P+G)[d]	3.9 4.5	2.3 3.1	0.1 1.4	0.2 1.3	4.2 4.8	1.0 1.1	1050 1150	-3.8 -2.0	464 601	—	—
All cast irons				3.5 4.5	0.7 3.1	0.1 1.5	0.1 1.3	4.2 4.8	1.0 1.1	1050 1150	-3.8 0.1	185 601	—	—

Notes

The two figures in the entries for composition, foundry properties, and mechanical properties represent the minimum and maximum range of values for each type of cast iron.

[a] Heat-affected plate C1 is omitted from the table.

[b] Composition range of the remaining elements is Si = 0.4 to 0.8%, S = 0.02 to 0.05%.

[c] C9 is a sprue.

[d] Brackets denote a small amount of the microconstituent.

326) and hardness (Donoho 1950: 98) of the material was estimated to be around 850 MPa.

The grey irons from Les Forges have hardness and strength comparable to Class 25 or 30 modern grey iron and represent a material of high quality that today would be considered satisfactory for engineering applications. Such a material was most suitable for tools, complex machine parts, and other objects that required considerable strength, wear resistance, and heat resistance, and very limited ductility or toughness. Modern engineering specification ASTM A 319-53 Class I recommends grey iron castings of a composition range similar to those from Les Forges for use at elevated temperatures. The main application of such material with thermal shock resistance is for firebox parts, grate bars, furnace parts, caustic pots, and melting pots. For example, plate C1, which had been affected by high temperatures, might have actually been used as a stove plate. The grey irons with a very hard and wear-resistant chill surface (as plates C1, C3, and C12), are well suited for manufacture of railway car wheels. The low-phosphorus grey irons C1 and C3 are sufficiently tough in the cast condition to be used for hammers and anvils.

In the white irons most of the carbon exists in the combined form as iron carbide. Because of the high proportion of this compound in ledeburite, the predominant phase, the white irons are hard and extremely brittle. This type of structure provides very high compressive strength and superior wear resistance, and retains its hardness up to a temperature somewhat higher than cherry-red heat of 700°C (*Gray and Ductile Iron Castings...* 1971: 272). The use of such a material must have been limited to special applications requiring high hardness values, excellent wear resistance, and good resistance to high temperatures, but no resistance to shock, due to its brittleness. The white irons, being more resistant to growth than the grey irons, could have been used, for instance, as plates in finery hearths.

The material characteristics are summarized in Tables 3 and 4, which recapitulate the structure, composition, foundry properties, and mechanical properties of the cast irons grouped according to archaeological period and to type of cast iron. The fact that this study deals not with finished cast objects but with artifacts in the form of plates, sprues, and runners should not make a significant difference in characterization of the material, assuming that the finished castings were not much larger in section thickness than the examined artifacts.

Method of Manufacture

Structure and composition provide information on the method of manufacture of the cast irons from Les Forges. Impurities in cast iron usually have their source in the ore and fuel used in the blast furnace and only rarely in the limestone flux.

The low sulphur content suggests the use of charcoal as fuel for the reduction of the cast irons. During smelting, phosphorus is reduced and taken up by the iron though a proportion of it finds its way into the slag. The high phosphorus content in the cast irons indicates that iron ores rich in phosphorus were used in their manufacture. High phosphorus and manganese contents seem to be common for bog-iron ores. The records (Griffin 1893: 974f., 990) show in fact that bog ores of the Trois-Rivières district were used for making chilled car wheels, stoves, and other high-quality castings. The large variations of phosphorus and manganese encountered in some of the cast irons might have resulted from the use of iron ores of different compositions, or possibly from the changing smelting conditions in the blast furnace. The very high carbon content present in the cast irons resulted from furnace conditions that secured plenty of the carbon that was available for solution by the iron. A high proportion of charcoal must have been used during smelting.

The silicon content is decided by the conditions of production, low temperatures favouring low-silica cast irons. The low silicon content in the cast-iron artifacts indicates a temperature ceiling in the smelting process. The lesser height and lower operating temperatures of the cold-blast furnace, employing bog-iron ore containing little gangue, tended to permit less absorption of silicon during smelting. This is in contrast to the higher silicon contents inevitable in a large modern blast furnace using ore from mines. The reduction of silica in such modern furnaces occurs in the bosh at a temperature greater than 1500°C.

Comparison with 18th- to 19th-century charcoal irons from various countries indicates that the Les Forges cast irons have considerably higher carbon content and generally higher manganese and phosphorus contents than are found in European or American cast irons (Table 5). The amount of silicon is similar and that of sulphur is commonly low. All this evidence shows that the cast irons from Les Forges are cold-blast charcoal irons, most of them being cold-short pig-iron grades.

In a modern blast furnace, coke or coal is used instead of charcoal, and when castings are made, the pig iron is remelted in a cupola or air furnace to modify the composition to what is finally desired. The composition of cupola cast iron, especially its carbon content, does not reach the upper limit of pig-iron composition. The carbon content of the cast irons from Les Forges is at, or exceeds, the upper limit of modern cast irons. This suggests that the molten iron was ladled from the open forehearth of the furnace and poured directly into prepared moulds on the casthouse floor. Production of liquid metal that could be cast into the desired shape was the main advantage that early blast furnaces had over the contemporary bloomeries.

The practical limit of maximum pouring temperature is determined by the ability of the mould to withstand the impact of the molten metal. This is in modern foundry practice about 1450 to 1500°C (American Society for Metals [hereafter cited as ASM] 1961–76, 1: 351). It can be argued, on the basis of the grey irons' structure, that the pouring temperature of the liquid metal was actually substantially below 1400°C. In cast iron the primary structure is greatly affected by the pouring temperature, and supercooling in the melting cycle would most likely result in undercooling during solidification. The absence in the structure of graphite flakes that are promoted by undercooling (Types D and E) (*Gray and Ductile Iron Castings*... 1971: 119f.), the small size of the eutectic cells, and the compact idiomorphic form of the manganese sulphide inclusions (Morrogh 1941b: 216) are signs that the grey irons from Les Forges were cast from near liquidus temperature, close to 1200°C. The pouring temperature of the white irons is expected to be higher than that of grey irons. This is substantiated by the presence in the white irons of a predominant columnar zone, as well as by their having a higher carbon equivalent and higher liquidus temperature than grey irons.

The composition and size of the cast-iron artifacts yield important technological clues. The grey and white irons have essentially the same range of composition, which is characterized by high carbon, low silicon, and varying manganese and phosphorus contents. In general the section thickness of the grey irons is smaller than that of the white and mottled irons. At

Table 5
Composition of 18th- to 19th-Century Charcoal Irons and Modern Cast Iron

	Britain					USA		Central Europe		Sweden		Russia		Modern		
Ref.*	1	2	3	3	4	5	5	6	6	7	8	9	9	10	11	12
Location	S. Staffordshire (avg. of 4)	Nibthwaite	Duddon (mottled)	Little Aston	Maryport (avg. of 4)	Hopewell, Ohio	Redding, Penn. (white)	Styria (white)	Joachimstahl (white)	Dannermora	Laxa	Woronez	Woronez	Grey (Class 20-60)	White	Mottled
C	3.07	3.86	4.30	3.37	3.89	4.07	3.99	2.93	3.60	4.81	3.55	3.32	3.00	2.50–3.80	1.8–3.6	3.25–3.60
Si	1.19	0.85	0.65	0.28	0.60	0.68	0.37	0.307	0.66	0.18	1.25	1.88	0.98	1.20–2.60	0.5–1.9	0.50–0.65
Mn	0.74	0.05	0.10	0.91	0.10	0.11	0.12	0.724	0.531	1.99	0.19	0.30	0.26	0.45–0.80	0.25–0.80	0.40–0.60
P	0.38	0.11	0.124	1.01	0.13	0.147	0.067	0.021	0.52	0.12	0.08	0.65	0.51	0.05–0.80	0.06–0.18	0.30–0.45
S	0.04	0.029	0.023	0.081	0.033	0.016	0.016	0.018	0.021	trace	0.04	0.030	0.035	0.05–0.13	0.06–0.20	0.15

**References*

1 Percy n.d.: 544
2 Morton 1969: 10
3 Morton and Gould 1967: 241
4 Tylecote et al. 1965: 871
5 Henger 1970: 47
6 Greenwood 1893: 65
7 Percy n.d.: 536 (no. 1)
8 Keep 1902: 11, 102
9 Eriksen and Thegel 1966: 82 (Gun 104, 103)
10 ASM 1961–76, 1: 355
11 *Gray and Ductile Castings*... 1971: 94
12 Heine, Loper, and Rosenthal 1967: 494

the same time, the section of most of the grey irons is larger than the minimum prevailing casting section size recommended by ASTM for Class 20 to 35 cast irons. The minimum section that can be cast grey and without massive free cementite is 3 to 9 millimetres (ASM 1961–76, 1: 353), while the average thickness of the grey iron artifacts is around 11 millimetres. It follows that the structure, the hardness, and the type of cast iron, as revealed by metallurgical examination of the artifacts, are basically not due to the artifacts' composition, but must have resulted from rapid cooling of the liquid metal. This suggests that different techniques were used in casting the grey irons and the white irons involving different rates of cooling, which was influenced by the type of mould and the temperature of the liquid metal.

The predominant presence of Type A graphite flakes and the absence of undercooled graphite in the pearlite matrix of the grey irons is a sign of moderate cooling, as in a loam or sand mould. Also, the presence of fine cellular structure is indicative of a moderately rapid cooling rate and of a relatively small section of the mould walls. The high carbon and low sulphur contents ensured that the charcoal irons solidified as grey irons in spite of their low silicon content. The white irons, on the other hand, were probably manufactured by casting the molten metal in a chilled mould, so that the cooling rate was high enough to produce white iron for the desired section size. Several factors contributed to the supercooling of the white irons. The presence of a predominant columnar zone in these irons is indicative not only of a relatively high pouring temperature, but also of very fast cooling, low alloy content, and possibly, keeping the top of the casting molten and at high temperature.

Technological Development of the Ironworks

Metallurgical examination did not produce evidence that would compromise the reported archaeological age of the cast-iron artifacts. In fact, their structure and composition are indicative of a certain pattern in the grouping of the cast irons. Comparison of the results of this study with the relative chronology of occupational layers shows that the cast irons from period I have a relatively low phosphorus content, whereas all the remaining irons from later periods, except C6, contain a much larger amount of phosphorus. This suggests that in the archaeological periods I or II there was a change in the type of ore used for manufacturing cast irons from low- to high-phosphorus iron ores. The cast irons from period I have varying structures, changing from one artifact to another. This might have been due to the lack of proper operational controls existing at that time in the manufacturing process.

All the irons from periods II and III, except C9, are white or mottled, most of them with a very high total carbon content. During these two periods a high proportion of fuel must have been used for smelting in the blast furnace. The last period (IV) distinguishes itself in phosphoric grey iron plates of uniform structure and composition. In transition between periods III and IV there was a change in casting technology from a chilled mould to a sand mould. According to Doat and Evrard (1951: 60), a time-related progression in types of cast iron produced was characteristic also for French, Belgian, and Luxembourgian foundrymen. They were casting parts in white iron in the 14th to 15th centuries, in mottled iron in the 16th to 17th centuries, and in grey iron at the end of the 17th century and throughout the 18th century. As far as other elements are concerned, there is no consistency in the large variations of manganese, and the low silicon content and very

low sulphur content remain basically at the same level throughout all archaeological periods.

In general the date of manufacture of a metal artifact cannot be determined from its structure or chemical composition alone. However, if the locality of its origin is known, the date of its manufacture may often be roughly estimated by comparing the results of an examination of a given artifact with the results of investigations of a series of artifacts of known dates from given localities or regions. No extensive metallurgical examination has been previously carried out on the cast irons recovered from the Les Forges ironworks, and consequently no reference basis was available for comparison with the data obtained here.

An attempt made in this study to date the cast irons by correlating the method of manufacture (including foundry properties, casting, and smelting conditions determined by means of metallurgical examination) with the technological development of the ironworks (known from the historical and archaeological sources) was only partially successful. This might be due to the lack of sufficently detailed information on the technological development of the site, or it may indicate that the change in technology reflected in the cast-iron artifacts was not drastic enough to warrant such an approach.

This study can serve as an information base for further investigation of artifacts from Les Forges. Its use for comparison purposes with other data is limited to the extent that the examination was carried out on a relatively small group of iron artifacts originating over a 150-year period. Only statistical-chronological series of metallurgical analyses combined with information supplied by archaeological research and historical sources will give a complete picture of the technological development of the site. Further investigation of archaeological material from Les Forges du Saint-Maurice is desirable and should be broadened to include finished objects, slag, ore, and furnace lining.

Glossary of Metallurgical Terms

For more information on technical terms, *see* the glossaries in American Society for Metals, *Metals Handbook*, Vol. 1, Properties and Selection of Metals (1961–76, 1: 1–41); W.K.V. Gale, *The British Iron and Steel Industry: A Technical History* (1967: 173–89); *Gray and Ductile Iron Castings Handbook* (1971: 649–68); Bruce A. Rogers, *The Nature of Metals* (1965: 303–13); and Leonard E. Samuels, *Optical Microscopy of Carbon Steels* (1980: 563–74). Also useful, especially to researchers working in other languages, is Eugeniusz Tyrkiel, *Dictionary of Physical Metallurgy: English, German, French, Polish, Russian* (1977).

ANISOTROPY. Here, the characteristic of a phase or inclusion having optical properties that vary according to the direction in which light is transmitted

ANNEALING. Heating to and holding at a suitable temperature (600–1000°C) and then cooling at a suitable rate (usually slow) for such purposes as softening a metal hardened by cold working, producing a desirable microstructure, or obtaining desired mechanical properties

AUSTENITE. Iron-rich solid solution containing carbon and having a face-centred cubic crystal structure

BLAST FURNACE. A shaft furnace supplied with an air blast and used to smelt iron ore to produce (liquid) pig iron

BLOOMERY. A primitive furnace for making wrought iron directly from iron ore

BOSH. The combustion zone of a blast furnace. It is the lower part of the shaft just above the hearth, where the walls begin to slope.

CARBON EQUIVALENT. The total carbon, silicon, and phosphorous values for a cast iron combined into a single factor influencing the eutectic composition and expressed in the form of an empirical relationship

CASTABILITY. A complex combination of liquid metal properties and solidification characteristics that promotes accurate and sound final casting

CAST IRON. A family of unmalleable casting alloys of iron with a high carbon content (usually from 1.7 to 4.5 per cent) and a considerable silicon content (0.5 to 2.6 per cent)

CEMENTITE (IRON CARBIDE). A very hard and brittle compound of iron and carbon, Fe_3C

CHARCOAL. Wood that has been distilled, leaving only carbon; formerly used as fuel in ironmaking.

CHILL. 1) A metal insert embedded in the surface of a sand mould or core, or placed in a mould cavity, to increase the cooling rate at that point. 2) A white iron structure that is produced in iron castings by rapid solidification caused, for example, by the use of a chill.

CHILLED CASTING. A casting that was cooled very rapidly and therefore possesses a very hard surface and a soft, tough interior

COLD-BLAST. Air that has not been preheated supplied under pressure to a blast furnace

COLD-SHORT. A condition of brittleness at temperatures below the recrystallization temperature of a metal

COLUMNAR STRUCTURE. A coarse structure of parallel columns of grains, each having its long axis perpendicular to the casting surface

COMBINED CARBON. The part of the total carbon in cast iron combined chemically with other elements and therefore not in the free state as

graphitic carbon. Graphitic carbon and combined carbon added together are equal to the total carbon content.

COMPRESSIVE STRENGTH. The maximum load per unit area that a brittle material can withstand without fracture when subjected to compression

CONSTITUENT. A phase or combination of phases that occurs in a characteristic configuration in an alloy microstructure

CRITICAL (TRANSFORMATION) TEMPERATURE. The temperature at which a change in phase, crystal structure, or physical properties occurs during the heating or cooling of a metal or alloy

CRYSTAL. A homogeneous solid of regular geometrical structure peculiar to the element and in which the atoms are spaced in characteristic pattern

CUPOLA. A small, coke-fired furnace for remelting pig iron for casting

DENDRITES. Crystals formed during solidification and characterized by a tree-like pattern composed of many branches

DIRECT (BLOOMERY) PROCESS. A single-stage reduction process of iron smelting directly from the ore. As a result of bloomery smelting, a pasty sponge of iron intermixed with slag is produced.

DIVORCED EUTECTIC. A structure in which the components of a eutectic appear to be entirely separate

DUCTILITY. The amount of plastic deformation that a material can withstand before fracture

ETCHING. The process of revealing structural details by preferential attack of reagents on a highly polished metal surface

EUTECTIC. A phase transformation in which all the liquid phase transforms on cooling to two solid phases simultaneously

EUTECTOID. A phase transformation in which a solid phase transforms on cooling to two different solid phases simultaneously

FERRITE. A solid solution of carbon in iron with a body-centred cubic crystal structure. It is nearly pure iron with less than 0.05 per cent carbon.

FINERY. A charcoal hearth used to purify pig iron to obtain wrought iron in the indirect process

FLAKE GRAPHITE. Graphitic carbon in the form of platelets, occurring in the microstructure of grey cast irons

FLUIDITY. The ability of liquid metal to flow readily, to run into and fill a mould cavity

FLUX. Material, like lime, added in an iron-making operation to combine with impurities and make slag flow easily

GANGUE. The commercially worthless mineral matter associated with economically valuable metallic minerals in an ore

GRAINS. Crystals in metals or alloys

GRAIN SIZE. The average size of the crystals or grains in metal

GRAPHITE. The uncombined carbon in cast irons

GRAPHITIZATION. The formation of graphite by the decomposition of cementite during the heating of cast iron

GREY CAST IRON. Cast iron that contains a relatively large percentage of carbon present in the form of flake graphite

GROWTH, CAST-IRON. Permanent increase in dimensions of cast iron resulting from repeated or prolonged heating at high temperatures

HARDNESS. Resistance of material to deformation, usually measured by indentation

HEARTH. The bed or working portion of any furnace. It holds the metal being heated or melted.

HOT-BLAST. A blast of air, preheated in a hot-blast stove, provided to a blast furnace to support combustion at a lower rate of fuel consumption and a higher production output than when using cold-blast

HYPEREUTECTIC. A composition to the right of the eutectic transformation point in a binary phase diagram

HYPOEUTECTIC. A composition to the left of the eutectic transformation point in a binary phase diagram

IDIOMORPHIC CRYSTAL. A crystal of definite external shape

INDIRECT PROCESS. A two-stage process of iron manufacture where liquid pig iron is made from ore by smelting and then purified by refining to wrought iron

INTERDENDRITIC. Located within the branches of a dendrite or between the boundaries of two or more dendrites

LEDEBURITE. Intimate eutectic mixture of austenite and cementite formed on rapid cooling of cast irons

LIQUIDUS. In a phase diagram, the upper line that is the locus of temperatures at which each alloy begins to solidify on cooling or stops melting on heating

MACROSTRUCTURE. Structure of metals as revealed on a ground or polished (and sometimes etched) specimen by the naked eye or under low magnification (up to ten diameters)

MATRIX. The principal, continuous constituent in microstructure in which other constituents or phases are embedded or enclosed

MICROCONSTITUENT. *See* PHASE and CONSTITUENT

MICROHARDNESS. The hardness of microconstituents of a material

MICROSTRUCTURE. The structure of a suitably prepared specimen as revealed at magnifications over ten diameters

MOTTLED CAST IRON. A mixture of grey iron and white iron in varying proportions

MOULD. The form, made of sand, metal, or refractory material, that contains the cavity into which molten metal is poured to produce a casting of desired shape

NONMETALLIC INCLUSIONS. Particles of impurities (usually silicates, sulphides, oxides, etc.) that are held mechanically or are formed during solidification or by subsequent reaction within the solid metal

ORE. A natural mineral deposit from which a useful, valuable metal can be extracted profitably

PEARLITE. Lamellar mixture of ferrite and cementite that results from the eutectoid decomposition of austenite in ferrous alloys and contains about 0.8 per cent carbon

PHASE. A constituent that is completely homogeneous both physically and chemically. It is separated from the rest of the alloy by definite boundary surface.

PHOSPHIDE EUTECTIC. *See* STEADITE

PIG IRON. The crude product of a blast furnace, run molten into a pig bed. It solidifies in side channels called sows, branching out into smaller channels called pigs

POROSITY. Holes in metal, not necessarily connected, caused by gas being trapped in molten or partially molten metal during solidification

PRIMARY CRYSTALS. The first type of crystals that separates from a melt on cooling

REFINING. The second stage of the indirect method of wrought-iron manufacture in which pig iron produced in a blast furnace is converted in a forge into wrought iron. The excess impurities (carbon, silicon,

manganese, phosphorous) are removed during remelting of the pig iron in the finery hearth, and the purified iron is forged in the chafery hearth to expell the slag and consolidate the metal.

REFLEX PLEOCHROISM. The property exhibited by certain optically anisotropic substances — when examined in plane polarized light — by which color and absorption of light depend on the orientation of the plane of polarization of incident light in relation to the crystal

RUNNER. 1) The horizontal channel through which molten metal flows into a mould. It connects the sprue with the casting. 2) The waste piece of metal cast in such an opening.

SHRINKAGE CAVITY. Void left in cast metals as a result of solidification shrinkage

SLAG. A nonmetallic, waste product formed during iron working, resulting from the action of a flux on the oxidized nonmetallic constituents of molten metals

SMELTING. A metallurgical operation in which the ore is reduced and the metal sought is separated from the gangue and from impurities with which the ore may be chemically combined or physically mixed

SOLIDIFICATION SHRINKAGE. The decrease in volume accompanying the freezing of a molten metal

SOLID SOLUTION. A crystalline phase in which a variable number of atoms of two metals can be distributed in a random fashion in one type of space lattice. In a solid solution the two metals are not combined chemically but exist dissolved in each other over a range of composition.

SPHEROIDITE (SPHEROIDIZED PEARLITE). A microstructure in which iron carbide occurs as small spheres in a ferritic matrix

SPRUE. 1) The vertical channel from the top of the mould that connects the pouring basin with the horizontal channel (the runner) leading the molten metal into the casting. 2) The waste piece of metal cast in such an opening.

STEADITE. A hard, phosphorus-rich microconstituent found in cast iron; ternary eutectic of austenite, cementite (Fe_3C), and iron phosphide (Fe_3P), or binary eutectic of ferrite and iron phosphide

STRUCTURE. The size, shape, and arrangement of phases

SUPERCOOLING. Cooling below the temperature at which an equilibrium phase change would take place without actually causing the transformation to occur

SUPERHEATING. Raising the temperature of molten metal above its normal melting temperature

TENSILE STRENGTH. The maximum normal load per unit area that a material will withstand prior to fracture when subjected to tension

THROAT. The narrowest part of the shaft, at the top of a blast furnace. The materials are loaded into the furnace through it.

TOUGHNESS. Ability of a material to absorb energy without failure

TUYÈRE. Opening through which the air blast enters any metallurgical furnace

WALLOON PROCESS. A two-hearth version of the finery process used in Belgium, Luxembourg, France, and Britain. Conversion of pig iron into wrought iron was done in the finery hearth using charcoal as fuel. Reheating for forging was done in the chafery hearth, where coal could be used.

WHITE CAST IRON. Cast iron in which all or substantially all of the carbon is in the combined form

WROUGHT IRON. A form of mechanically shaped pure iron with threads of slag or cinder

References

American Society for Metals
1961–76
Metals Handbook. 8th ed. Metals Park, Ohio. 11 vols. Vol. 1 [1961]: Properties and Selection of Metals.

Bailey, Alan R, and Leonard E. Samuels
1971
Foundry Metallography. Metallurgical Services, Betchworth, Eng. Annotated Metallographic Specimens: Special Series — Studies in Technology.

Beaudet, Pierre
1983
"The Saint-Maurice Ironworks, Canada." *Historical Metallurgy*, Vol. 17, No. 1 (Jan.), pp. 39–41. East Haney, Eng.

Bérubé, André
1983
"Technological Changes at Les Forges du Saint-Maurice, Quebec, 1729–1883." *CIM Bulletin/Bulletin ICM*, Vol. 76, No. 853 (May), pp. 75–80. Montreal.

Cox, Richard
1977
"Les forges du Saint-Maurice." *Research Bulletin/Bulletin de recherches*, No. 51. Parks Canada, Ottawa.

Doat, Robert, and René Evrard
1951
"Three Centuries of Cast Iron Metallurgy." *American Foundryman*, Vol. 20, No. 2 (Aug.), pp. 58–60. Des Plaines, Ill.

Donoho, C.K.
1950
"Mechanical Testing and Properties of Gray Iron." *Foundry*, Vol. 78, No. 6 (June), pp. 96–99, 218–19. Cleveland.

Eriksen, Egon, and Svend Thegel
1966
Conservation of Iron Recovered from the Sea. Nordlunde, Copenhagen. Tøjhusmuseets Skrifter 8.

Gale, W.K.V.
1967
The British Iron and Steel Industry: A Technical History. David and Charles, Newton Abbot, Eng.

Gray and Ductile Iron Castings Handbook; Including Data on Gray, Ductile, White and High Alloy Irons
1971
Ed. Charles F. Walton. Gray and Ductile Iron Founders' Society, Cleveland.

Greenwood, William Henry
1893
Steel and Iron, Comprising the Practice and Theory of the Several Methods Pursued in their Manufacture.... 6th ed. Cassel & Company, London.

Griffin, P.H.
1893
"The Manufacture of Charcoal-Iron from the Bog- and Lake-Ores of Three Rivers District, Province of Quebec, Canada." *Transactions of the American Institute of Mining Engineers*, Vol. 21, pp. 974–92. Philadelphia.

Hamaker, John C., Jr., William P. Wood, and Franklin B. Rote
1952
"Internal Porosity in Grey Iron Castings." *Transactions of the American Foundrymen's Society*, Vol. 60, pp. 401–27. Chicago.

Harrington, B.J.
1874
"Notes on the Iron Ores of Canada and Their Development." In Canada. Geological Survey of Canada, *Report of Progress for 1873–74*, Dawson Brothers, Montreal, pp. 192–259.

Heine, Richard W., Carl R. Loper Jr., and Philip C. Rosenthal
1967
Principles of Metal Casting. McGraw-Hill, New York.

Henger, G.W.
1970
"The Metallography and Chemical Analysis of Iron-Base Samples Dating from Antiquity to Modern Times." *Bulletin of the Historical Metallurgical Society*, Vol. 4, No. 2, pp. 45–52. England.

Humphreys, J.G.
1961
"Effect of Composition on the Liquidus and Eutectic Temperatures and on the Eutectic Point of Cast Irons." *British Cast Iron Research Association Journal*, Vol. 9, No. 5 (Sept.), pp. 609–21. Birmingham.

Keep, William J.
1902
Cast Iron: A Record of Original Research. J. Wiley and Sons, New York.

Krause, D.E.
1969
"Gray Iron — A Unique Engineering Material." *ASTM Special Technical Publication*, No. 455, pp. 3–28. Philadelphia.

McGain, Alison
1977.
"Travaux d'hiver aux Forges du St-Maurice, 1977." *Research Bulletin/Bulletin de recherches*, No. 68. Parks Canada, Ottawa.

MacKenzie, J.T.
1946
"The Brinell Hardness of Gray Cast Iron and Its Relation to Some Other Properties." *Proceedings — American Society for Testing Materials*, Vol. 46, pp. 1025–35. Philadelphia.

Miller, Harry
1968
Canada's Historic First Iron Castings. Queens' Printer, Ottawa. Department of Energy, Mines and Resources, Information Circular IC 209.

Morrogh, H.
1941a
"The Polishing of Cast-Iron Micro-Specimens and the Metallography of Graphite Flakes." *Journal of the Iron and Steel Institute*, Vol. 143, No. 1 (Aug.), pp. 195–205. London.
1941b
"The Metallography of Inclusions in Cast Irons and Pig Irons." *Journal of the Iron and Steel Institute*, Vol. 143, No. 1 (Aug.), pp. 207–53. London.

Morton, George R.
1969
"Technical Aspects of the Early Iron Industry of Furness and District." *Bulletin of the Historical Metallurgical Society*, Vol. 3, No. 1, pp. 6–11. England.

Morton, George R., and J. Gould
1967
"Little Aston Forge: 1574–1798." *Journal of the Iron and Steel Institute*, Vol. 205, No. 3 (March), pp. 237–44. London.

Nadon, Pierre
1977
"Recherches archéologiques aux Forges de Saint-Maurice (1973–1976)." *Research Bulletin/Bulletin de recherches*, No. 44. Parks Canada, Ottawa.

Percy, John
n.d.
Metallurgy. Facs. of 1861–80 ed. 4 vols. Vol. 2 [1864]: Iron, Steel. De Archaeologische Pers Nederland, Eindhoven.

Rogers, Bruce A.
1965
The Nature of Metals. Paperback ed. MIT Press, Cambridge, Mass.

Samuels, Leonard E.
1980
Optical Microscopy of Carbon Steels. American Society for Metals, Metals Park, Ohio.

Schneidewind, Richard, and R.G. McElwee
1950
"Part I: Composition and Properties of Gray Iron; Part II: Correlation of Properties of Gray Irons." *Transactions of the American Foundrymen's Society*, Vol. 58, pp. 312–32. Chicago.

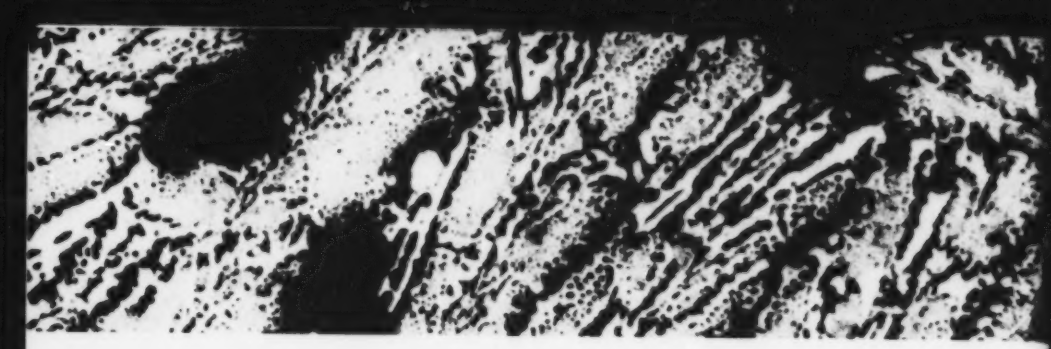
Swank, James M.
n.d.
History of the Manufacture of Iron in All Ages and Particularly in the United States from Colonial Times to 1891.... Facs. of 1892 ed. Burt Franklin, New York. Burt Franklin: American Classics of History and Social Sciences Series 6.

Trottier, Louise
1980
"Les Forges du Saint-Maurice: Their Historiography." *History and Archaeology*, No. 42. Ottawa.

Tylecote, Ronald F., A.P. Banks, D.R. Wattleworth, and B.G. Ashmore
1965
"Maryport Blast Furnace: Post Mortem and Reconstruction." *Journal of the Iron and Steel Institute*, Vol. 203, No. 9 (Sept.), pp. 867–74. London.

Tyrkiel, Eugeniusz
1977
Dictionary of Physical Metallurgy: English, German, French, Polish, Russian. Elsevier Scientific Publishing, Amsterdam.

Unglik, Henry
1987
"Metallurgical Investigations of Cast Irons from Les Forges du Saint-Maurice Ironworks, Quebec, Canada." *Historical Metallurgy*, Vol. 21, No. 1 (Jan.), pp. 1–7. East Haney, Eng.



Metallurgical examination of 12 artifacts recovered from Canada's first ironworks at Les Forges du Saint-Maurice, Quebec, showed them to be grey, white, and mottled cast irons.

The cast irons were produced in a charcoal blast furnace operating at low temperatures. They are cold-blast charcoal irons. Differences in structure, composition, and technology of the irons were linked to the four occupational periods of Les Forges: I, 1667–1760; II, 1760–1800; III, 1800–1850; and IV, 1850–1883. Irons from period I are of varying structures. With one exception the iron from periods II and III is white or mottled. In periods I or II the type of ore changed from low to high phosphorous. Between periods III and IV casting technology changed from chilled moulds to sand moulds. Period IV is marked by phosphoric grey iron plates of uniform structure and composition.

Canada